Measurement Techniques, Vol. 54, No. 10, January, 2012

THE CALIBRATION OF GRADIENT HEAT FLUX SENSORS

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UDC 536.087.92

Test benches for calibrating heat flux sensors at temperatures of 500–1000 K are described, and the results of such calibrations are presented.
Keywords: *heat flux, sensor, heat measurement, calibration.*

Gradient heat flux sensors (GHFS) are comparatively new measuring instruments. They have been used in thermal experiments since 1996 [1, 2], but they are not yet part of a number of standard measuring instruments, which is slowing down the development of gradient heat measurements both in thermal experiments and in many areas of technology. In this connection, the calibration of GHFS is an important problem, which has yet to obtain a satisfactory solution.

The volt-watt sensitivity of a GHFS is expressed in the form

$$S_0 = E/(q_z F),$$

where E and F are the thermoelectric EMF and the area of the heat flux sensor in plan, and q_z is the heat flux density.

Since standard heat-flux sensors have not yet been constructed, the calibration is constructed by comparing the signal E with the heat flux $q_z F = UI$, where U and I are the voltage drop and the current strength in a standard heater. This arrangement of the experiment is one in which one can take into account and minimize the losses, connecting the Joule–Lenz power of the source with the generated heat flux.

For comparatively low temperatures (approximately up to 500 K), the calibration is carried out on a test bench (Fig. 1*a*), first described by Divin [3]. Battery GHFS, based on anisotropic single crystals of bismuth, were calibrated by an absolute method: under steady heat conditions the heat flux density was kept unchanged with time and was the same over the whole plane of the sensor. The calibrated GHFS *4* was placed on a base *5*. The heat flux source was an electric heater *3*; its power was determined by the current strength and the voltage drop, maintained by the "guard" heater *1*, at a zero value of the heat flux through the additional GHFS *2*, which perform the functions of a null indicator.

The "extraneous" losses of heat flux in this arrangement do not exceed 0.5 W. Calibration is possible up to the melting point of bismuth (271°C). The linearity of the calibration characteristic (Fig. 1*b*) is maintained at an external pressure of up to 30 MPa; the change in sensitivity of the GHFS as a function of the temperature does not exceed 3%.

The voltage, resistance, and current strength were measured using a TsUIP digital universal measuring instrument (TU11-DEMO.341.000 TU-80).

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Translated from Izmeritel'naya Tekhnika, No. 10, pp. 36–38, October, 2011. Original article submitted June 14, 2011.

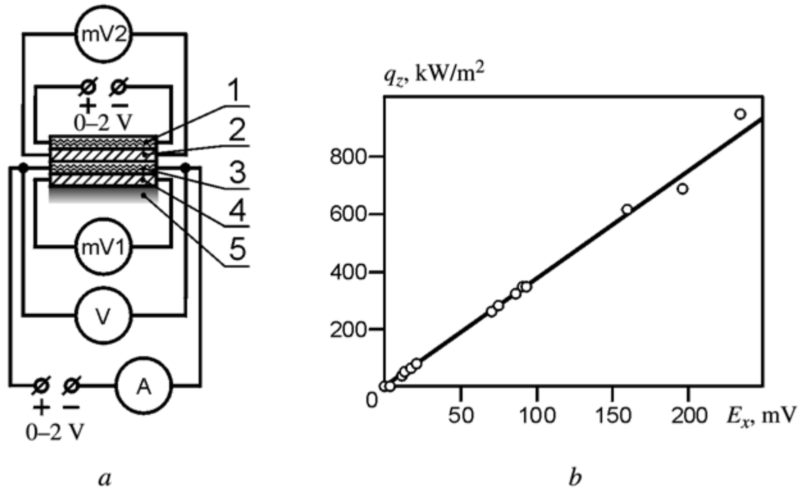


Fig. 1. Sketch of the calibration test bench (*a*) and the results of the calibration of a typical GHFS made of bismuth (*b*), where the points denote data obtained by an alternative method: *1*) "guard" heater; *2*) additional GHFS in the zero-indicator function; *3*) heater; *4*) calibrated GHFS; *5*) base.

The overall standard uncertainty with which the volt-watt sensitivity S_0 of the GHFS is known, is expressed as

$$\Delta S_0 = \sqrt{\left(\frac{\partial S_0}{\partial E}\Delta E\right)^2 + \left(\frac{\partial S_0}{\partial Q}\Delta Q\right)^2}.$$

In this method, the heat flux Q was determined from the Joule–Lenz power N of the heater after deducting the heat loss from the side surfaces of the calibration module:

$$Q = N - Q_\mathrm{f},$$

where $N = U^2/R$, R is the ohmic resistance of the heater, and Q_f is the heat flux, connected with the heat dissipated into the surroundings.

During the course of preliminary experiments, we established that Q_f amounts to not more than 0.5 W, while the overall stationary uncertainty of their estimate does not exceed ±10%.

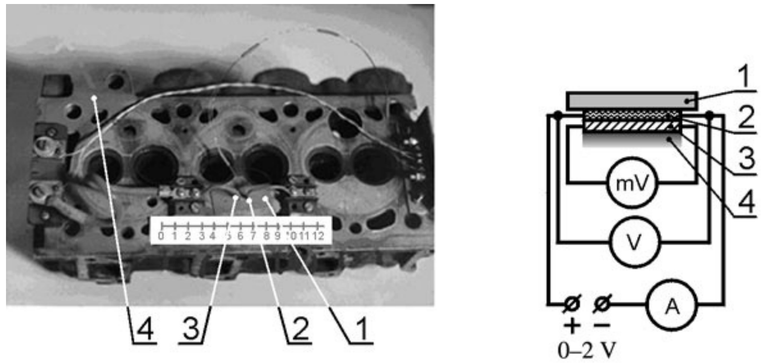
The overall standard uncertainty of the Joule–Lenz power is

$$\Delta N = \sqrt{\left(2\frac{U}{R}\Delta U\right)^2 + \left(-\frac{U^2}{R^2}\Delta R\right)^2},$$

while the overall standard uncertainty of the heat flux is

$$\Delta Q = \sqrt{\left(\frac{\partial Q}{\partial N}\Delta N\right)^2 + \left(\frac{\partial Q}{\partial Q_\mathrm{f}}\Delta Q_\mathrm{f}\right)^2}.$$

Taking into account the metrological characteristics of the instruments used $S_0 = 6.04\cdot10^{-5}$ V/W, while the relative error in determining S_0 is $\Delta S_0/S_0 = 0.64\%$.



a *b*

Fig. 2. Sketch of the calibration of the GHFS proposed in this paper: *a*) arrangement of the elements on the stand; *b*) basic circuit; *1*) thermal insulation; *2*) heater; *3*) calibrated GHFS; *4*) base.

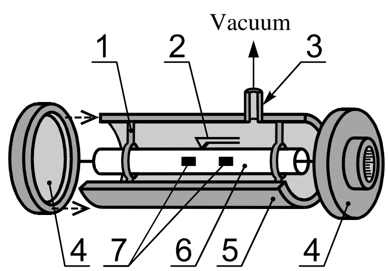


Fig. 3. Sketch of the test bench for the high-temperature calibration of the GHFS: *1*) holder; *2*) thermocouple; *3*) tube for evacuating the system; *4*) covers; *5*) body; *6*) tube; *7*) GHFS to be calibrated.

The values of U, I, and R employed in the calculation correspond to the most “difficult” conditions for calibration (the dimensions of the GHFS in plan were 10 × 10 mm, and their temperature was about 250°C), and hence in the remaining cases the relative error of the calibration does not exceed the value given.

This calibration system is not the only one. In the experiments, the GHFS *3* with dimensions in plan of 4 × 7 mm was placed on a massive base of Silumin (silicon-aluminum alloy) *4* (Fig. 2). The heater *2*, mounted on a plate *1* of glass-textolite, which is a nichrome plate with dimensions of 4 × 7 × 0.04 mm, was placed on top of the GHFS *3*. Copper wires with a cross section of 2 mm^2 were fed through the opening in the glass-textolite. The calibration module is closed with a layer of thermal insulation.

The heater *2* was supplied with a dc current from a battery (12 V, 66 A·h) through a rheostat. The supplied power was varied using the rheostat and was monitored with a voltmeter and an ammeter. The maximum power dissipated in the heater was 30 W, which, when converted to the area of the GHFS, corresponds to a heat flux density of $1.07 \cdot 10^6$ W/m^2. The GHFS signal was recorded by a V7-42 millivoltmeter.

The calibration curve, obtained using the Divin test bench, and our experimental points are compared in Fig. 1*b*. The spread in the experimental points from the mean linear characteristic in the 293–544 K temperature range lies in the range 0.2–1.0% over the major part of the characteristic and reaches 6–8% upwards on the right. In this region, the temperature of the whole assembly exceeds 200°C and hence the systematic error of what is clearly a rough experiment reduces its accuracy. However, the calibration using both circuits gives satisfactory agreement of the results.

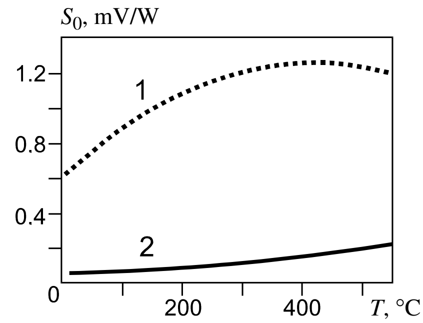


Fig. 4. Calibration curves for the GHFS: *1*) 12N18Kh9T steel + nickel;
2) chromel + alumel.

It is impossible to calibrate the GHFS at high temperatures using the above methods: the losses from convective heat exchange and radiation increase, and the thermal stability of the materials is insufficient. To solve this problem, we designed a new test bench (Fig. 3) and developed the procedure described below.

The test bench is a cylindrical body *5* made of steel, on the axis of which a tube *6* made of nickel foil with a tungsten heater inside is fixed in special holders *1*. The calibrated GHFS *7* and a thermocouple *2* are placed on the surface of the tube. The body *5* is closed with covers *4* and hermetically sealed with silicone. On one of the covers *4* there is a hermetic joint for providing power to the heater and for taking off the signals from the GHFS and the thermocouple. The test bench is evacuated through the tube *3*, which enables convective heat exchange to be eliminated: the heat flux from the heater is transferred by radiation in the radial direction. The thermocouple *2* is used to determine the reference temperature.

The signal from the GHFS is expressed by the formula $E = S_0 qF$, while the power provided by the heater is $P = UI$. The heat flux density on the surface of the tube *6* can then be represented as

$$q = \frac{P}{\pi dl} = \frac{UI}{\pi dl},$$

where d and l are the diameter and length of the tube (d = 15 mm and l = 220 mm).

Hence, the volt-watt sensitivity of the GHFS is

$$S_0 = E\pi dl/(UIF).$$

The heater is fed from the 220 V ac power supply through an autotransformer. The power dissipated $P = UI$ is monitored by a voltmeter and an ammeter. In the tests, the maximum power was 190 W, which corresponds to a heat flux density of 22.5 kW/m^2. The GHFS signals were applied to a PCLD-789D switch circuit board, and from it to a PCL-818HG analog-to-digital converter and was processed in the Genie medium.

The low thermal resistances of nickel foil, of which the tube *6* (see Fig. 3) was made, and of the GHFS themselves *7* enabled us to carry out the calibration under dynamic conditions: the signals of the calibrated sensors *7* and of the thermocouple *2* were recorded in synchronism. The symmetry of the circuit enables several sensors to be calibrated simultaneously.

For an area $F = 45.5\cdot10^{-6}$ m^2, the overall standard uncertainty $\Delta F = 1.38\cdot10^{-7}$ m^2. The overall standard uncertainty of the calculation of the heat flux density Δq = 261 W/m^2, while that of the volt-watt sensitivity is $\Delta S_0 = 6.8\cdot10^{-6}$ V/W. The relative error in determining the volt-watt sensitivity is equal to 6.75%, which exceeds the requirements of the metrological apparatus. It is proposed to improve the test bench later; it is primarily necessary to thermostat the heat-sensing surface of the body *5* (for example, using a water cooling jacket).

The results of the calibration of a GHFS made of a 12Kh18N9T steel + nickel composite and chromel + alumel are shown in Fig. 4, after averaging and removal of the noise and harmonics, induced from the supply (50 Hz) network. As follows from Fig. 4, in the 250–400°C temperature range, which is of the greatest interest for heat measurement, for example, in the heating of a boiler, the characteristic of a GHFS made of a chromel + alumel composite is monotonic, but the sensitivity of the sensors made of a 12N18Kh9T steel + nickel composite is higher by almost an order of magnitude, which makes this GHFS preferable under conditions of industrial experiments.

The next stage of the investigation will be to construct a module for calibrating a GHFS at temperatures up to 600°C with a relative error not greater than 5%.

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